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MAGNETIC RADIATION SHIELDING

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ABSTRACT

Recent discoveries of superconducting alloys with high critical current density in high magnetic fields offer the possibility of shielding manned space vehicle cabins from Van Allen belt radiations, solar flares, and cosmic ray primaries. Magnetic fields of suitable geometries could deflect incoming charged particles to shield a region of space from particles with energy up to perhaps a billion electron volts. The possibility of replacing a massive material shield by a lighter magnetic shield generated by superconducting coils is examined.

INTRODUCTION

Energetic charged particles from various sources in space require heavy shielding to protect the crew of a space vehicle from radiation damage (ref. 1). The high proton fluxes of the Van Allen belts necessitate either shielding or rapid traversal. Trips of a few weeks duration (e.g., to the moon) require shielding from solar flare protons. Longer trips of 2 or 3 years require heavier shielding to protect the crew from the less frequent, but more energetic, giant solar flares and from cosmic ray primaries. Discouragingly large masses of shielding are required to reduce the crew's radiation dose to a tolerable level. Deflecting the charged particles with magnetic fields has been suggested, but if normal conductors are used in the coils, the system would weigh more than a thick material shield giving the same protection (ref. 2). However,

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superconducting coils, which require power only for startup and for refrigeration, may offer a lighter total system than a material shield. This paper considers a few configurations for these coils and the advantages and disadvantages of each.

Elementary Types of Deflecting Fields

Axially symmetric fields, such as a dipole field, the field of a circular loop, and finite and infinite solenoids, achieve various degrees of shielding. The magnetic dipole shields an approximately toroidal-shaped region around it from all particles below a "threshold" energy, as shown in figure 1. A circular turn shields a toroidal region enclosing the turn (fig. 2). Both of these fields extend to infinity and therefore exert forces on incoming particles over large distances. This might be called external deflection. A finite solenoid will produce external deflection, but, in addition, its internal field can deflect particles (except those incident along the axis) so they do not penetrate into a smaller region in and around the solenoid axis. The infinite solenoid (fig. 3)(a practical impossibility, of course) would work only by internal deflection, since it has no external field. A second type of coil which would use internal deflection is a toroidal coil such as shown in figure 4(a). Two modes of shielding are possible with this configuration. If the dimension D in figure 4(a) is large, the coil resembles an infinite solenoid and has similar shielding properties. On the other hand, if the coil is deformed as in figure 4(b), the field-free region on the toroid axis can be shielded.

Choosing a field from the many possibilities involves the following considerations:

(1) The object of shielding is to reduce the radiation dose received by a human occupant of a space vehicle from a level which might be fatal for a long unshielded mission down to a tolerable level (ref. 1). Because the flux of charged particles in cosmic rays and in solar flares falls off rapidly with increasing energy, it is possible to pick a "threshold" energy level for a space mission such that, if all particles of lower energy are not allowed to penetrate into the crew compartment, the total number of higher energy particles which do reach the crew during the entire mission will be small enough to produce only a tolerable radiation dose. This threshold level lies somewhere in the range of 100 Mev to 1 Bev, depending on the mission duration. A magnetic shield must be able to exclude particles having the threshold energy appropriate for the duration of the mission.

(2) Since the whole point in considering magnetic shields is to minimize shield mass, the lowest possible mass is a primary goal.

(3) A field-free shielded volume would be preferred, because intense fields affect instrumentation and might also have undesirable affects on the crew over long periods of time.

(4) From the point of view of navigation, a coil with a dipole moment is undesirable, since magnetic fields present in space, such as the Earth's field or the field associated with a solar flare, will produce torques on the coil. On the other hand, if the particles in the initial phase of a solar flare are directional rather than isotropic, a torque tending to aline the axis of the coil with the field due to the stream of particles might increase the shielding effectiveness (ref. 3).

A few coil types will now be considered with these guiding principles in mind.

Infinite Solenoid

An infinitely long solenoid cannot actually be built, of course, but its shielding effects and its weight are easier to evaluate than those of other magnetic shields. The characteristics of the large-diameter toroidal coil are essentially those of the infinite solenoid. An infinite solenoid would completely shield a cylindrical region inside it from all particles with energies below a certain "threshold" level. The threshold energy is that for which a particle incident in a plane perpendicular to the axis and at grazing incidence (path g, fig. 3) is bent so that it just misses the shielded volume. More energetic particles will be excluded if their velocity component in a plane perpendicular to the axis is no greater than the "threshold velocity," which is the velocity of a particle of threshold energy. Further, any angle of incidence other than grazing improves the shielding effectiveness. Therefore, there is partial shielding against particles of energy greater than the threshold energy.

It is interesting for comparison purposes to calculate the solenoids weight per unit length. If J_c is the critical current density for the superconducting material, then the thickness t of the solenoid winding must be at least $t = B/\mu_0 J_c$ to carry enough current to produce the field B.[1] The mass M_{sc} of conducting material per unit length of solenoid is then

$$M_{sc} = 2\pi b t \rho_{sc} = \frac{2\pi b \rho_{sc} B}{\mu_0 J_c}$$

where b is the solenoid radius, and ρ_{sc} is the density of the superconducting material. To exclude particles of threshold energy T, we must

[1] mks units are used in all formulas.

have $b = a + 2R$, where a is the radius of the shielded volume, and R is the cyclotron radius of the particle of energy T in the field B. Therefore,

$$M_{sc} = \frac{2\pi}{\mu_0} \frac{\rho_{sc}}{J_c} (aB + 2P)$$

where $P = RB$ is a constant depending only on T and the particle mass and charge. The mass of structural material M_{st} necessary to withstand the hoop stress due to magnetic forces is (per unit solenoid length)

$$M_{st} = \frac{\pi}{\mu_0} \left(\frac{\rho_{st}}{S_y}\right) (aB + 2P)^2$$

where ρ_{st} is the density of the structural material and S_y is its tensile yield stress. If a field-free shielded region is desired, a second solenoid, surrounding the shielded region and carrying a current in the opposite direction to the shield current, will nullify the field. The additional mass penalty per unit length for structure and superconducting material is

$$\frac{\pi}{\mu_0} \frac{\rho_{st}}{S_y} \alpha B^2 a^2 + \frac{2\pi}{\mu_0} \frac{\rho_{sc}}{J_c} Ba$$

where α is an appropriate number greater than 1 such that a stiffened tube under external compressive pressure P must weigh α times the weight of the same diameter tube which can withstand an internal pressure P. The sum of conductor and structure weight for a solenoid with a field-free shielded region is given in figure 5 for a field B of 1 w/m^2 and 500 Mev as the proton threshold energy for $a = 2m$. The lines plotted in the figure give the weight of that portion of an infinite solenoid which is long enough to enclose the shielded volume given by the abscissa.

Magnetic Dipoles, Circular Loops, and Short Solenoids

At distances large in comparison with their size the magnetic dipole, the circular loop, and the short solenoid produce identical deflections of charged particles. Hence to particles of low energy, which cannot approach the coils very closely, these three types of fields are indistinguishable. However, determining the shielding effectiveness for higher energy particles requires individual treatment of each field. The exclusion of charged particles from regions of space around a magnetic dipole (fig. 1) has been investigated by Stormer (and reported in ref. 4) to explain the existence and nature of the aurorae. Levy has used a similar technique to study shielding due to a circular loop (ref. 3). The technique depends on being able to write a reasonably simple expression for the vector potential of the current distribution. For the circular loop the vector potential involves an elliptic integral. For a more extended current distribution like the short solenoid, the expression is correspondingly more complex and should yield information only with considerably more difficulty. However, because of its similarity to a simple circular loop, the short solenoid would probably have rather similar shielding properties. Levy estimates the total weight of a single loop which would shield an approximately toroidal volume as shown in figure 2. His estimates for the weight, including refrigeration and structure to withstand the stresses, are shown in figure 5.

Toroidal Geometries

A toroidal coil, deformed as shown in figure 4, produces internal deflection. The shielded volume is field-free, and there is no external field. A problem in this type coil is that particle paths of types a and b in figure 4(b) can occur. Path a occurs because the field B varies inversely with distance from the symmetry axis, and therefore the radius of curvature of the trajectory is smaller near the axis. The field can be made nearly constant in magnitude by modifying the windings so that they take the form of coaxial cylindrical tubes carrying appropriate currents which are returned on the surface of the sphere, as in figure 6. This shield might be called a constant-field toroidal shield. Type a paths cannot occur in this field. Type b paths can still occur and must be eliminated in some manner, perhaps by some kind of cap over one end, but this problem will not be considered here.

A rough estimate of the weight of the constant-field system can be found by considering the system of figure 7, which has closely spaced coaxial current tubes surrounded by a sphere to return the currents. If the average current density in the space in and around the tubes is $J = B/\mu_0 r$, where r is a cylindrical coordinate, the field will be of uniform magnitude inside the sphere. The mass M_{sc} of superconducting material needed in the tubes and in the sphere to carry this current can be found to be

$$M_{sc} = (\pi + 4) \frac{\pi}{\mu_0} \left(\frac{\rho_{sc}}{J_c}\right) \frac{(aB + 2P)^2}{B}$$

where a and b are the shielded region radius and the shield outer radius, respectively. It is assumed that J_c is 1.3×10^9 amperes per square meter at B = 8.8 Webers per square meter, and that J_c varies approximately as $B^{-0.6}$, which is a reasonable extrapolation of the best results for J_c in the superconducting compound Nb_3Sn as reported in reference 5. The magnetic forces act on the sphere in a direction normal to the sphere and on the tubes inward toward the axis. The mass of structure to withstand the forces can be estimated if assumptions are made about the supporting methods. Suppose that the axial component of the force on the sphere is withstood by tension in the tubes and the radial component (in cylindrical coordinates) by hoops in planes perpendicular to the axis. Suppose that the compressive forces on each tube are withstood by a structure whose mass is α times the mass of a tube which could withstand the same radial stress in expansion rather than compression. The structural mass is then

$$M_{st} = \frac{4\pi}{3\mu_0}\left(\frac{\rho_{st}}{S_y}\right)(1 + \alpha)\frac{1}{B}(aB + 2P)^3$$

For a given radius of the shielded volume the optimum field strength B to minimize M_{st} is $B = P/a$, for which

$$M_{st} = \frac{36\pi}{\mu_0}\left(\frac{\rho_{st}}{S_y}\right)(1 + \alpha)aP^2$$

This mass estimate states that, for a given threshold energy, the structure mass is proportional to the radius of the shielded volume. The sum of the structure and conductor masses of a constant-field toroidal shield versus the shielded volume is shown in figure 5 for $\alpha = 2$. An estimated insulation and refrigeration mass is included in the plotted values and in most cases is less than 10 percent of the total mass.

Unusual Requirements of Magnetic Shields

The high intensity and large volume of the fields required in magnetic shields automatically create some unusual problems concerning current and energy. For example, the constant-field toroidal shield may store several billion joules of energy, which must be supplied when the shield is started. If we assume that on the average during startup one-half of the available power is fed into the field and one-half is dissipated in the power supply and controlling circuits, then building up the field will require a length of time $t = 2\,\frac{\text{final stored energy}}{\text{power}}$. For a stored energy of two billion joules and a 10-kilowatt power supply, this time is 55 hours.

Although building up the field may take considerable time, an accident which destroys the superconductivity of a part of the windings may lead to a rapid and destructive release of the energy. Two billion joules of energy introduced into the structure by eddy currents from the decaying field could raise the temperature of 100,000 pounds of metal hundreds of degrees Kelvin, possibly melting or even vaporizing parts of the structure. It would be difficult to predict what forces might be produced during the decay, but these could increase the destructiveness. To prevent such a mishap the coils might be wound in many separate circuits, each carrying independently a part of the total current. If the operating current in each circuit is safely below the critical current, failure of one circuit would induce exactly enough current in the other circuits to maintain the original field.

Very large currents are needed to produce the field in any magnetic shield. The constant-field toroidal shield requires around 50 million ampere turns. Even if a large number of turns is used, say 5000, the startup power supply must have a large current capacity, in this case, 10,000 amperes. The circular loop shield requires comparable currents (ref. 3). In the previous discussion the weight and nature of the startup power supply have not been considered. It would be hoped and it seems reasonable to expect that its weight would be small compared with the large weight of the structure. If not, it might be left behind after startup and therefore not constitute a burden during the space voyage.

Discussion and Summary

Figure 5 shows that magnetic shields may be lighter than shields of absorbing material. Since most of the mass in each type of magnetic shield considered was in structural material, an improvement in strength to weight ratio would be beneficial. Special techniques such as using fine filaments instead of bulk materials to withstand hoop stresses might significantly reduce structure weight. In some cases such as the circular loop, it might be possible to reduce the weight by constructing a partially force-free winding.

Each shield type considered has disadvantages. Infinite solenoids are impossible. However, the toroidal coil resembles the solenoid if its major diameter is large. But this requirement of large diameter means that only very large volumes can be shielded. Thus, for volumes of less than several thousand cubic meters the low weights of the infinite solenoid (fig. 5) cannot be realized. The circular loop produces an undesirable field in the shielded volume. Further, this volume is toroidal in shape and thus might be more difficult to utilize efficiently than a spherical or cylindrical volume. The deformed toroidal coil of figure 6 has none of these disadvantages, but the problem of eliminating type b paths (fig. 4(b)) has not been examined and remains to be solved.

All magnetic shields should perform somewhat better than the foregoing discussion indicates. Most shields exclude all radiation below a threshold level, and this level has been used for comparison with material shields. Since each shield has some effectiveness at shielding from particles of higher energy than the threshold, the resulting dose to a man would be less than one would expect if the shielding effectiveness ceased abruptly at the threshold energy.

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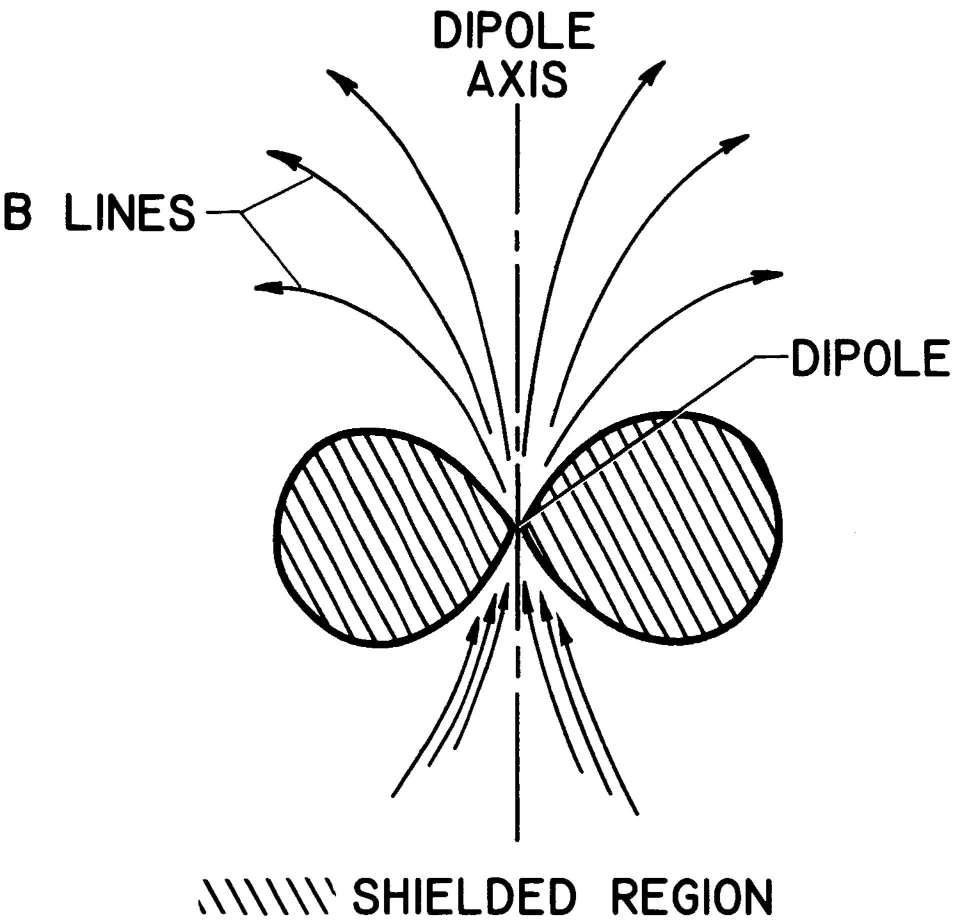

Fig. 1. Shielded region around a dipole (cross section through dipole axis).

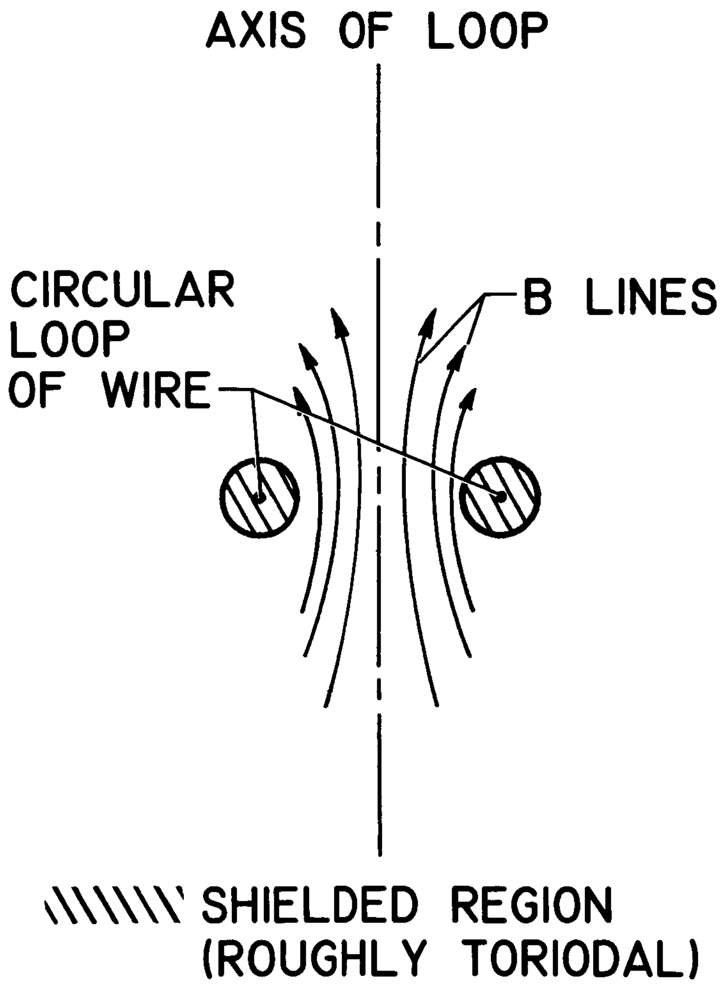

Fig. 2. Shielded region of a circular loop (cross section through axis of loop).

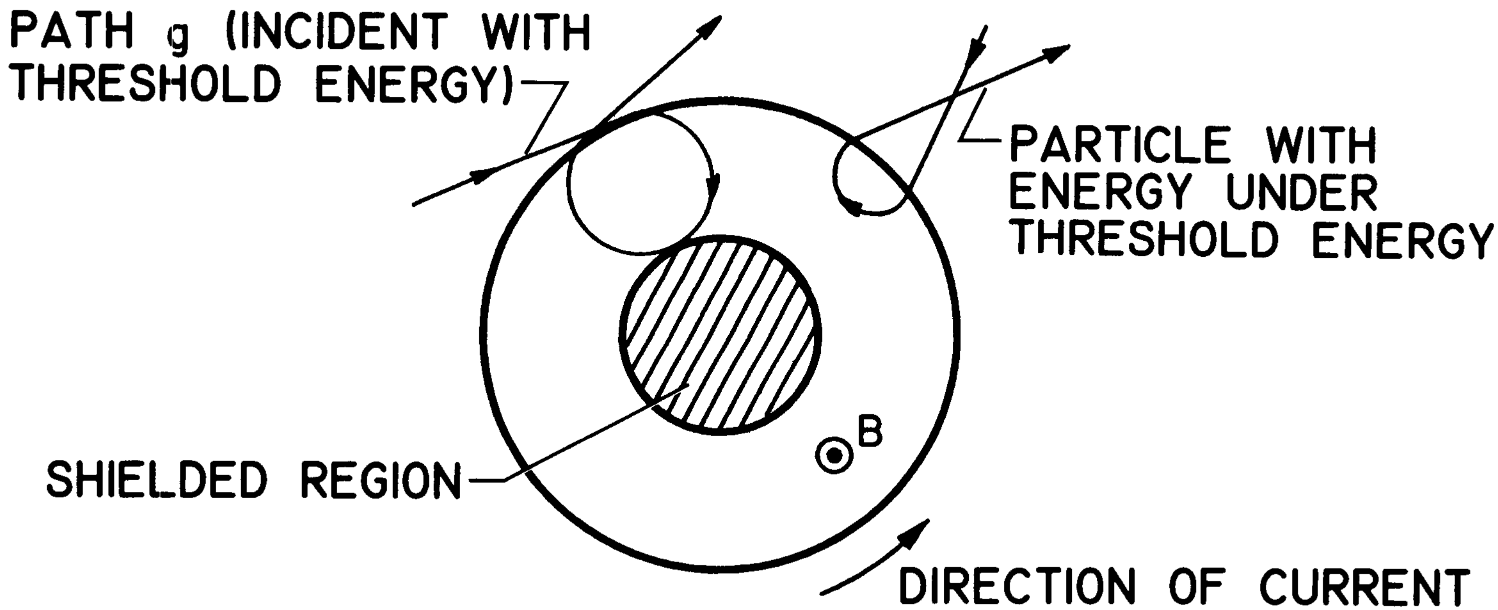

Fig. 3. Infinite solenoid shield (section perpendicular to axis).

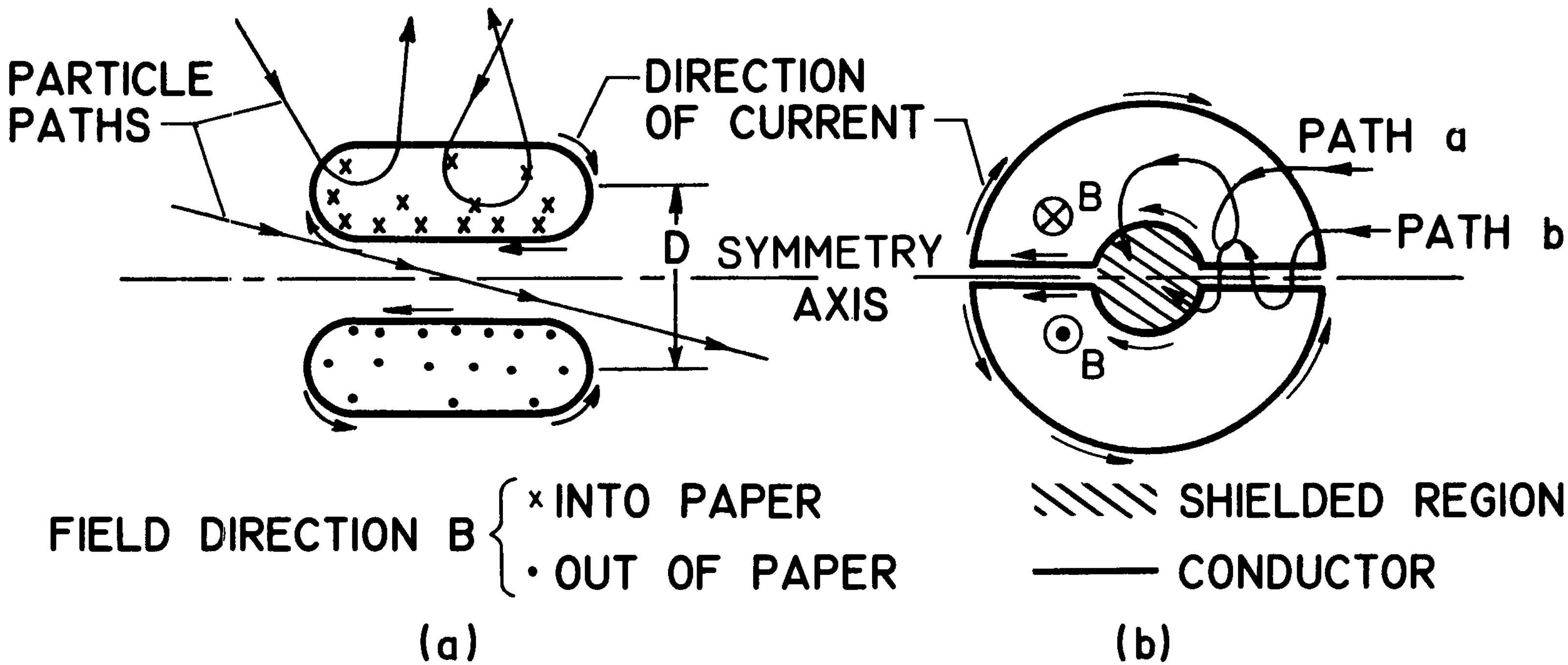

Fig. 4. Deformation of a toroidal coil from Form (a) to Form (b), which shields a spherical volume (section through axis of rotational symmetry).

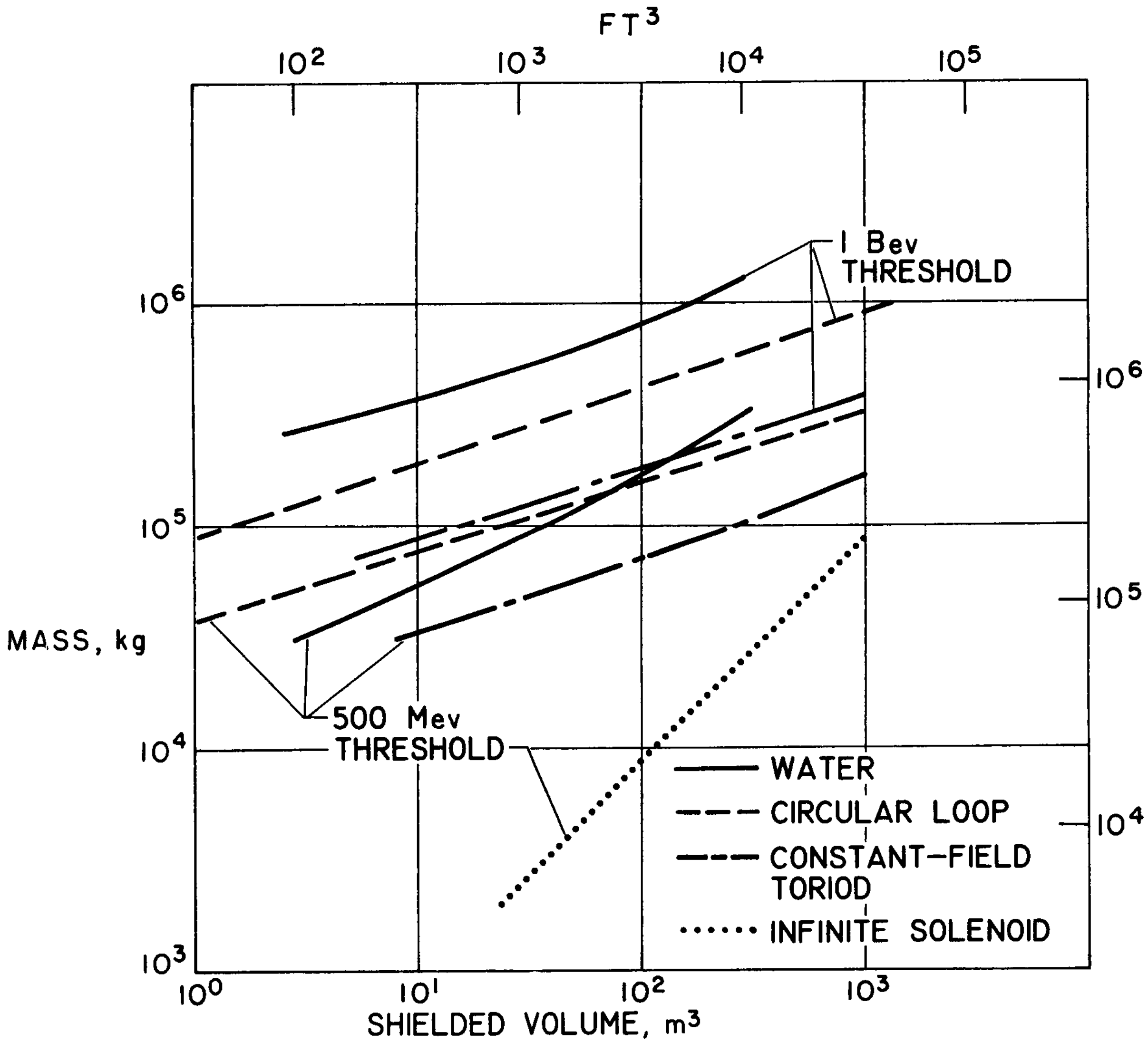

Fig. 5. Shield mass vs. shielded volume for magnetic and water shields.

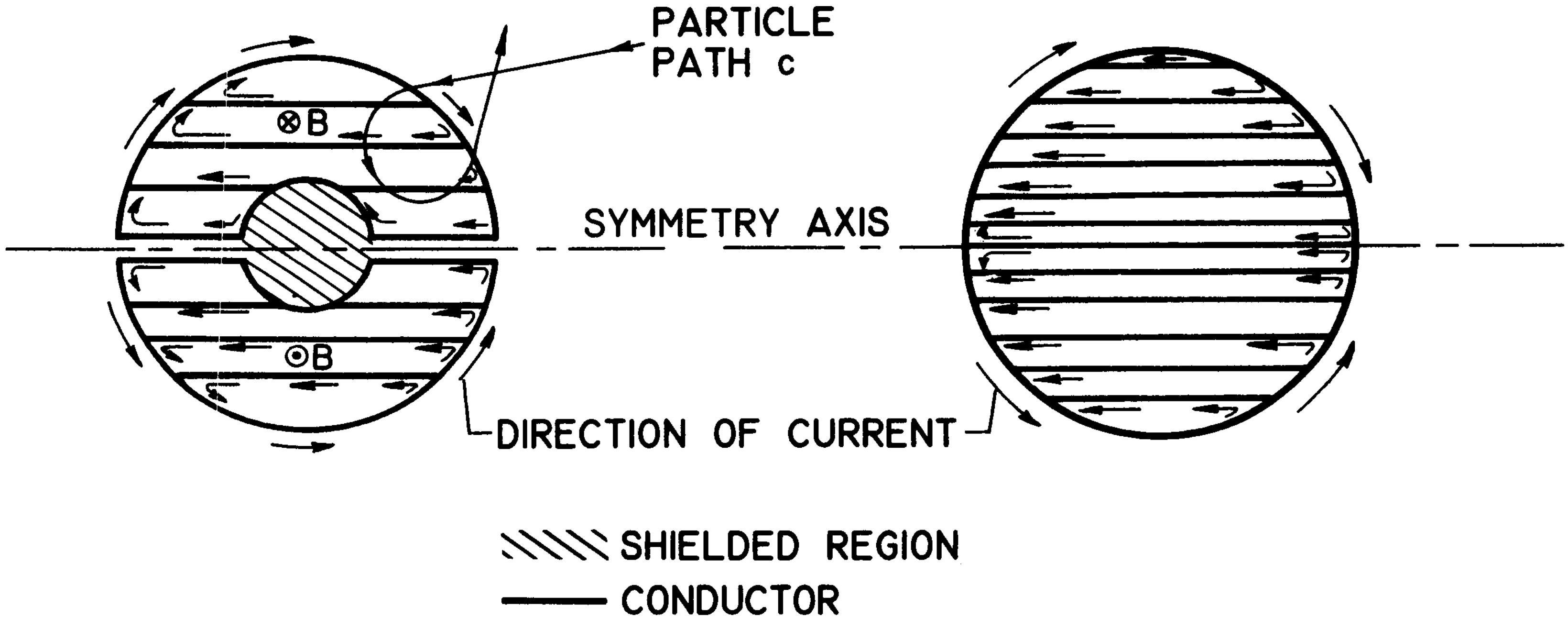

Fig. 6. "Constant-field" toroidal shield, showing four concentric tubes (section through axis of rotational symmetry).

Fig. 7. Idealization of "constant-field" toroidal shield (for weight estimation).